

Citation for published version:

Gonzalez, J & Wallis, G 2021, 'Carb-conscious; The role of carbohydrate intake in recovery from exercise', *Current Opinion in Clinical Nutrition and Metabolic Care*, vol. 24, no. 4, pp. 364-371.
<https://doi.org/10.1097/MCO.0000000000000761>

DOI:

[10.1097/MCO.0000000000000761](https://doi.org/10.1097/MCO.0000000000000761)

Publication date:

2021

Document Version

Peer reviewed version

[Link to publication](#)

Publisher Rights

CC BY-NC

This is a pre-copy-editing, author-produced PDF of an article accepted for publication in *Current Opinion in Clinical Nutrition and Metabolic Care* following peer review. The definitive publisher-authenticated version Gonzalez, Javier T.; Wallis, Gareth A. Carb-conscious, *Current Opinion in Clinical Nutrition and Metabolic Care*: May 10, 2021 - Volume Publish Ahead of Print - Issue is available online at: https://journals.lww.com/co-clinicalnutrition/Abstract/9000/Carb_conscious__the_role_of_carbohydrate_intake_in.98984.aspx

Gonzalez, Javier T.; Wallis, Gareth A. Carb-conscious, *Current Opinion in Clinical Nutrition and Metabolic Care*: May 10, 2021 - Volume Publish Ahead of Print - Issue - doi: 10.1097/MCO.0000000000000761

University of Bath

Alternative formats

If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

TITLE:

Carb-conscious; The role of carbohydrate intake in recovery from exercise

AUTHORS:

Javier T. Gonzalez^{1,2} and Gareth A. Wallis³

AFFILIATIONS:

¹Department for Health, University of Bath, Bath, UK.

²Centre for Nutrition, Exercise and Metabolism, University of Bath, Bath, UK.

³School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, Birmingham, UK.

CORRESPONDING AUTHOR:

Javier T. Gonzalez

Department for Health,

University of Bath,

Bath,

BA2 7AY

Email: J.T.Gonzalez@bath.ac.uk

Tel: 0(+44)1225 385518

ABSTRACT

Purpose of review

This review summarised evidence on the role of carbohydrates in recovery from exercise within the context of acute and chronic effects on metabolism and performance.

Recent findings

Recent studies demonstrate that, in contrast to recovery of muscle glycogen stores, the recovery of liver glycogen stores can be accelerated by the co-ingestion of fructose with glucose-based carbohydrates. Three recent studies suggest this can extend time-to-exhaustion during endurance exercise tests. However, periodically restricting carbohydrate intakes during recovery from some training sessions to slow the recovery of liver and muscle glycogen stores may, over time, result in a modest increase in the ability to oxidise fat during exercise in a fasted state. Whether this periodised strategy translates into a performance advantage in the fed state remains to be clearly demonstrated.

Summary

To maximise recovery of glycogen stores and the capacity to perform in subsequent endurance exercise, athletes should consider ingesting at least 1.2 g carbohydrate per kilogram body mass per hour - for the first few hours of recovery - as a mixture of fructose and glucose-based carbohydrates. However, if a goal is increased capacity for fat oxidation, athletes should consider restricting carbohydrate intakes during recovery from some key training sessions (**Supplemental video abstract**).

Keywords

Fructose; Glucose; Glycogen; Metabolism; Nutrition

Introduction

Carbohydrates are a major fuel during almost all exercise intensities, both with and without carbohydrate feeding [1-7]. Accordingly, each bout of exercise with training and competition is likely to result in at least some degree of whole-body carbohydrate depletion. Modest amounts of carbohydrates can be synthesised by gluconeogenesis, yet dietary carbohydrate intake is essential for rapid replenishment of carbohydrate stores, especially when the recovery timeframe is limited [8]. Recovery is multifaceted, encompassing many physiological (and other) factors such as rehydration, restoration of acid-base balance, and the repair of muscle damage. Whilst carbohydrate intake could influence many of these factors, this brief review will focus specifically on the acute restoration of glycogen stores and the associated recovery of acute physical performance. In addition, since the rate of repletion of endogenous carbohydrate stores may have the potential to influence longer-term adaptations to training, the role of the replenishment of carbohydrate stores on acute intramuscular signalling events, and longer-term adaptations will be discussed.

Post-exercise muscle glycogen synthesis is reliant more on the quantity, than the specific type of carbohydrate ingested

In humans, carbohydrates are stored endogenously as glycogen, primarily in muscle, but also in the liver, with smaller amounts in other tissues such as the kidneys and brain. Muscle and liver glycogen are known to be quantitatively important for sustaining the energy demands of moderate-to-high exercise intensities [4,8-10]. However, as endogenous glycogen stores are relatively small, the availability of glycogen can limit exercise capacity when the duration is prolonged (>90 mins). Furthermore, when optimal performance is required repeatedly within a relatively short timeframe (i.e. within 24 hours), then the restoration of glycogen stores between bouts of exercise becomes a key factor dictating the capacity for subsequent performance [8]. Therefore, it is pertinent to consider how the

quantity and the type of carbohydrates ingested can affect recovery of glycogen stores after exercise.

Current sports nutrition guidelines, such as the joint position statement from the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine state that for “Speedy refuelling” athletes should aim for carbohydrate intakes of between 1-1.2 g per kg body mass per hour for the first four hours post-exercise [11]. There is no specific emphasis on the types of carbohydrates to be consumed other than combinations of drinks and foods to meet targets and that moderate-to-high glycaemic index carbohydrates may be useful [11]. This statement is in line with the evidence on carbohydrate ingestion for muscle glycogen repletion, whereby muscle glycogen repletion rates show linear increases with carbohydrate ingestion rates up to an ingestion rate of 1-1.2 g per kg body mass per hour, thereafter, muscle glycogen repletion rates plateau [12]. Furthermore, the current evidence suggests that as long as a readily available source of substrate for muscle glycogen synthesis is provided which elicits a robust insulin response, the type of carbohydrate plays little role in muscle glycogen repletion rates, at least when the total amount of carbohydrate ingested meets recommendations [13].

Understanding liver glycogen metabolism cannot be simply extrapolated from evidence collection on muscle glycogen metabolism

In contrast to the substantial evidence base on carbohydrate ingestion and post-exercise recovery of muscle glycogen stores, there is much less evidence on the role(s) of the quantity and type of carbohydrates for post-exercise recovery of liver glycogen stores. Moreover, the responses of liver glycogen resynthesis in the acute post-exercise period are markedly different to that of muscle glycogen resynthesis, and thus the evidence on muscle glycogen recovery cannot be immediately generalised to liver glycogen recovery [13]. For

example, muscle glycogen repletion rates are known to show the most rapid resynthesis rates in the early (<2 h) post-exercise period – sometimes referred to as the insulin-independent phase - and substantially slow down thereafter (**Figure 1A; data from [13]**). Furthermore, this pattern is consistent whether the carbohydrates ingested in recovery are glucose-based carbohydrates alone, or a combination of glucose and fructose-based carbohydrates. In contrast, liver glycogen repletion rates demonstrate a reverse pattern, whereby liver glycogen repletion rates are slower in the first 2 hours post exercise than they are in hours 2-5 post-exercise (**Figure 1B; pooled data from [13,14]**). The mechanisms underlying this reverse pattern compared to muscle glycogen repletion are not immediately clear, especially as both muscle and liver glycogen are thought to display autoregulation (i.e. glycogen synthesis is stimulated by low glycogen concentrations, and glycogenolysis is stimulated by high glycogen concentrations). However, it is possible that the post-exercise hormonal milieu, at least in part, explains why liver glycogen concentrations recover more slowly in the earlier *versus* later post-exercise period.

Liver glycogen concentrations are determined by the net balance between glycogen synthesis and glycogenolysis. In humans, both glycogen synthesis and glycogenolysis occur simultaneously and therefore glycogen turnover rates can be substantial. These processes are in turn, regulated by a variety of factors including the availability of key hormones (e.g. insulin, glucagon and epinephrine), and metabolites (e.g. glucose, non-esterified fatty acids, lactate). Insulin and glucagon display counter-regulatory effects, whereby insulin stimulates glycogen synthesis and suppresses glycogenolysis, and glucagon stimulates glycogenolysis whilst inhibiting glycogen synthesis. Interestingly, during a hyperglycaemic (10.4 mmol/L), clamp where peripheral insulinaemia was held at 192 pmol/L (likely to result in basal or mild hyperinsulinaemia at the portal vein), restoring glucagon concentrations within a physiological range from a suppressed $\sim 30 \text{ pg} \cdot \text{mL}^{-1}$ to a basal $\sim 65 \text{ pg} \cdot \text{mL}^{-1}$ resulted

in a suppression of net glycogen synthesis from $\sim 20 \text{ mmol} \cdot \text{L}^{-1} \cdot \text{h}^{-1}$ to $\sim 12 \text{ mmol} \cdot \text{L}^{-1} \cdot \text{h}^{-1}$, which was explained by both a suppression of glycogen synthesis and a stimulation of glycogenolysis [15]. Therefore, liver glycogen concentrations seem to be regulated in some ways differently to muscle glycogen concentrations which would not be expected to be influenced by circulating glucagon. Therefore nutritional (and other) recommendations for liver glycogen recovery need to be based on evidence from the measurement of liver glycogen concentrations in humans.

Adding fructose to glucose-based carbohydrates accelerates post-exercise recovery of liver glycogen stores without compromising muscle glycogen recovery

In addition to the liver demonstrating a different time course of glycogen repletion compared to muscle, liver glycogen resynthesis rates also respond differently to muscle with respect to the types of carbohydrates consumed. Whereas muscle glycogen repletion rates seem to be insensitive to the presence or absence of fructose, liver glycogen resynthesis rates are potentially enhanced when fructose (or galactose) are mixed with glucose-based carbohydrates [13]. Accordingly, for maximal recovery of both muscle and liver glycogen stores, athletes should consider including fructose (and/or galactose) within their recovery strategies.

Adding fructose to glucose-based carbohydrates in post-exercise recovery enhances subsequent time-to-exhaustion

Optimized recovery of both muscle and liver glycogen stores by combined post-exercise feeding of glucose-fructose based carbohydrates could be expected to enhance subsequent exercise performance. This has been investigated in a limited number of studies which are summarised in **Table 1**. Combined glucose-fructose post-exercise - as compared to glucose-only based carbohydrate feeding - has been reported to improve subsequent

endurance time-to-exhaustion in three studies [3,16] . In one of these studies carbohydrate oxidation rates during subsequent fixed-intensity exercise were sustained for longer with post-exercise glucose-fructose feeding, providing some evidence that higher carbohydrate availability underpinned the endurance benefit [3]. No differences in whole-body carbohydrate oxidation between conditions were observed in two cycle ergometer-based studies, despite post-exercise glucose-fructose feeding resulting in enhanced subsequent endurance time-to-exhaustion [3]. The similar substrate oxidation response may be explained by a higher exercise intensity (80% vs. 70% VO_2max) and much shorter time-to-exhaustion (i.e., 23-36 vs. 61-81 min) in the cycle ergometer studies. It had been suggested that improved gastro-intestinal comfort could be a feature of the ergogenic benefit of post-exercise glucose-fructose feeding although the cycle ergometer-based studies did not support this [3]. Overall, it seems clear that post-exercise glucose-fructose feeding can improve endurance time during subsequent exercise.

In contrast, after high-intensity intermittent cycle ergometer exercise performed until voluntary exhaustion, subsequent time-to-complete a pre-loaded cycle time trial commenced 4 h later was similar regardless of post-exercise carbohydrate type [17]. Notably, carbohydrate oxidation rates appeared higher during a 60 min moderate intensity (50% Wmax) steady state exercise bout performed immediately prior to the time trial with post-exercise glucose-fructose feeding as compared to glucose only. This could have negated any potential benefit of enhanced carbohydrate storage in recovery from exercise with glucose-fructose feeding. In another study, combined glucose-fructose provision after small-sided rugby training matches did not enhance markers of performance in subsequent training matches performed 3 h later [18]. Post-exercise glucose-fructose feeding was provided at sub-optimal ingestion rates (i.e., $0.8 \text{ g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$) and also combined with protein co-ingestion; a strategy that has not yet been demonstrated to result in superior liver and

muscle glycogen synthesis. Both of these studies involved performance assessments that required participants to self-regulate their exercise intensity, whereas those studies where a benefit of post-exercise glucose-fructose feeding was observed employed fixed-intensity exercise performed until voluntary exhaustion. Whether this explains the varying outcomes of the studies or indeed other aspects of study design such as the overall duration or intensity of the subsequent exercise bout, the carbohydrate dose ingested, or the presence/absence of other nutrients remains to be tested. Collectively, while from a limited number of studies, the data suggests that post-exercise glucose-fructose feeding is at least as effective as glucose-only based carbohydrate for subsequent exercise performance, and in some situations glucose-fructose may provide further advantages.

Restricting carbohydrate in post-exercise recovery can augment intramuscular signalling in relation to exercise adaptation

Due to the importance of carbohydrates for sustaining exercise performance, a traditional view has been that athletes should optimise carbohydrate availability for all training sessions in order to maximise the capacity for training volume. This view has evolved into a periodized carbohydrate availability paradigm, whereby athletes may specifically choose to restrict carbohydrates at key times in the season, or even at key times within a day (before, during, or in recovery from a bout of exercise) [19,20]. Therefore, some athletes may aim not to recover endogenous carbohydrate stores as quickly as possible post-exercise, either to prolong the time-period on which the muscle is exposed to a low-glycogen state, and/or to produce a lower-glycogen status when commencing the next training session. The physiological evidence supporting this approach comes from studies demonstrating that restricting carbohydrates before, during, or after a single bout of exercise can result in greater exercise signalling within skeletal muscle and adipose tissue, such as increased mRNA expression and or protein content/phosphorylation status of genes involved in energy

sensing, mitochondrial biogenesis, fatty acid and glucose metabolism [21,22]. However, it should be noted that enhanced intramuscular mRNA signalling responses have not always been observed under conditions of differing glycogen concentrations or with altered carbohydrate availability [21,23-25].

Periodically restricting carbohydrates in recovery can augment intramuscular adaptations and whole-body fat oxidation in response to exercise training

When carbohydrate availability is manipulated in recovery over a period of training in order to commence some training sessions with low muscle and/or liver glycogen availability, a number of enhanced muscular adaptations have been observed, including increased activity of mitochondrial enzymes [26], increased basal muscle glycogen and GLUT4 content [21,22], and increased whole-body fat oxidation rates [26,27]. Evidence suggests that these augmented adaptation with restricting carbohydrate availability may be due to the higher fatty acid availability as well as the lower carbohydrate availability per se, with implications for glucose feeding during exercise [22]. In support of this, an overnight fast prior to exercise - which does elevate plasma NEFA availability but does not drastically alter muscle glycogen concentrations – is sufficient to augment skeletal muscle adaptations in AMPK and GLUT4 protein content following exercise training [21], although a high-fat meal does not augment skeletal muscle exercise signalling acutely [28]. Another approach which may hold promise for augmenting adaptations to training whilst also supporting the carbohydrate requirements of exercise could be delayed feeding, i.e. commencing exercise in a state of relative glycogen depletion and only beginning to ingest carbohydrates after the first hour of exercise [20]. Nevertheless, to-date, this has only been tested in the context of acute exercise and training studies are required to establish if the strategy does augment adaptation or performance responses to training.

Whilst there seems to be a relatively small but consistent response of higher fat oxidation rates with periodising carbohydrate intakes, the performance effects in athletes are still equivocal. A handful of studies have assessed the performance effects of training with consistently high *versus* periodised carbohydrate intake for at least 3 weeks [26,27,29-32]. These span cycling, triathlon, and race-walking. When the data from these studies are pooled, fat oxidation rates are increased with periodised carbohydrate availability compared with high-carbohydrate availability from $\sim 5 \text{ mg}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ to $\sim 8 \text{ mg}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (**Figure 2**; weighted means across studies). For context, in the same studies, a chronically low-carbohydrate, high-fat diet increased fat oxidation rates to $\sim 23 \text{ mg}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. In contrast, the change in performance was +6% with both high-carbohydrate and periodised carbohydrate availability, whereas the change in performance was -2% with a low-carbohydrate, high-fat diet; and this performance decreases can persist in even in the presence of glycogen restoration [33]. Notably, the majority of these studies examined fat oxidation rates during a fasted state. Therefore, it remains to be clearly established whether periodising carbohydrate intake alters substrate metabolism during exercise in a fed state. In the one study that has assessed substrate metabolism in the fed state, no differences between high carbohydrate *versus* periodised carbohydrate were detected [29].

Conclusions

Exercise is a potent challenge to endogenous carbohydrate stores. Muscle and liver glycogen stores are depleted with typical endurance training and competition. Rapid recovery of these stores is a key goal during competition and in some training blocks, yet to achieve some training goals, the recovery of muscle and/or liver glycogen stores may be consciously delayed. When aiming to maximise the recovery of both muscle and liver glycogen stores, current evidence would suggest that athletes should aim to ingest at least 1.2 g carbohydrate per kg body mass per hour for the first four hours of recovery; and using

a mixture of fructose and glucose-based carbohydrates will further accelerate the recovery of liver glycogen stores and can improve subsequent time-to-exhaustion during some endurance tasks. Specifically restricting carbohydrate in recovery from some training sessions can be used as an approach to augment some intramuscular adaptations to training, and can also modestly increase whole-body fat oxidation rates during exercise in a fasted state. However, whether periodically restricting carbohydrates in this way can increase either fat oxidation rates or endurance performance in the fed-state is currently unclear.

Key points

- Restoration of endogenous carbohydrate (glycogen) stores is a key component of short-term recovery from endurance exercise
- The replenishment of glycogen stores can be accelerated when fructose is co-ingested alongside glucose-based carbohydrates
- Fructose co-ingested with glucose-based carbohydrates in recovery from exercise can also enhance subsequent time-to-fatigue
- Periodically restricting carbohydrates in recovery from some training sessions can modestly increase the capacity for fat oxidation during exercise in a fasted state
- Whether periodically restricting carbohydrates in recovery from some training sessions can increase fat oxidation or exercise performance in a fed state is currently unclear.

Acknowledgements

We apologize for being unable to cite older papers (i.e., before 2018) that contributed to the progress of this field due to restrictions in the number of older publications that can be included to the references list.

Financial Support and Sponsorship

No specific funding was received for the preparation of this article. JTG has received research funding from Arla Foods Ingredients (DK), LucozadeRibena Suntory Ltd (UK) and Kenniscentrum Suiker & Voeding (NL). GAW has received research funding from GlaxoSmithKline Ltd (UK), LucozadeRibena Suntory Ltd (UK), Dairy Management Incorporated (USA), and Volac International Ltd (UK).

Conflicts of Interest

JTG has acted as a consultant for PepsiCo (UK). GAW has acted as a consultant for Sugar Nutrition UK, and received speakers honoraria from the Gatorade Sports Science Institute (USA) and the Utrecht Group (NED).

References

- *1. Menzies C, Wood M, Thomas J, Hengist A, Walhin JP, Jones R, Tsintzas K, Gonzalez JT, Betts JA (2020) Frequent Carbohydrate Ingestion Reduces Muscle Glycogen Depletion and Postpones Fatigue Relative to a Single Bolus. *Int J Sport Nutr Exerc Metab*:1-7. doi:10.1123/ijsnem.2019-0291

This study demonstrated that ingesting carbohydrate at regular intervals early on in running, extends time-to-exhaustion compared to an isocaloric bolus of carbohydrate late on in exercise.

- *2. Barber JFP, Thomas J, Narang B, Hengist A, Betts JA, Wallis GA, Gonzalez JT (2020) Pectin-Alginate Does Not Further Enhance Exogenous Carbohydrate Oxidation in Running. *Med Sci Sports Exerc* 52 (6):1376-1384. doi:10.1249/MSS.0000000000002262

This study demonstrated that glucose fructose mixtures enhance exogenous carbohydrate oxidation rates during running, with no further increase by the addition of pectin and alginate to create carbohydrate hydrogels.

**3. Gray EA, Green TA, Betts JA, Gonzalez JT (2019) Post-exercise glucose-fructose co-ingestion augments cycling capacity during short-term and overnight recovery from exhaustive exercise, compared to isocaloric glucose. International Journal of Sport Nutrition and Exercise Metabolism. doi:10.1123/ijsnem.2019-0211

This study demonstrated that the improvement in subsequent exercise capacity when fructose-glucose mixtures are ingested in recovery from exercise translates to cycling and also persists when the recovery period spans overnight. This provides practical relevance for multi-stage endurance events.

*4. Rollo I, Gonzalez JT, Fuchs CJ, van Loon LJC, Williams C (2020) Primary, Secondary, and Tertiary Effects of Carbohydrate Ingestion During Exercise. Sports Med 50 (11):1863-1871. doi:10.1007/s40279-020-01343-3

The paper reviewed the mechanisms by which carbohydrate ingestion improved endurance performance.

*5. Smith HA, Hengist A, Bonson DJ, Walhin JP, Jones R, Tsintzas K, Afman GH, Gonzalez JT, Betts JA (2021) Muscle Glycogen Utilization during Exercise after Ingestion of Alcohol. Med Sci Sports Exerc 53 (1):211-217. doi:10.1249/MSS.0000000000002458

This study demonstrated that a modest dose of ethanol ingested before cycling does not alter muscle glycogen utilization during exercise.

*6. Narang BJ, Wallis GA, Gonzalez JT (2020) The effect of calcium co-ingestion on exogenous glucose oxidation during endurance exercise in healthy men: A pilot study. Eur J Sport Sci:1-9. doi:10.1080/17461391.2020.1813336

This study demonstrated that the addition of calcium to glucose ingested during exercise does not increase exogenous glucose oxidation rates.

*7. Odell OJ, Podlogar T, Wallis GA (2020) Comparable Exogenous Carbohydrate Oxidation from Lactose or Sucrose during Exercise. Med Sci Sports Exerc 52 (12):2663-2672. doi:10.1249/MSS.0000000000002426

This study demonstrated that exogenous oxidation rates of lactose ingested in moderate amounts during exercise do not differ from sucrose.

*8. Fuchs CJ, Gonzalez JT, van Loon LJC (2019) Fructose co-ingestion to increase carbohydrate availability in athletes Journal of Physiology. 597(4): 3549-3560. doi:10.1113/JP277116

This paper reviewed the effects of fructose-glucose co-ingestion on recovery of glycogen stores after endurance exercise.

*9. Edinburgh RM, Hengist A, Smith HA, Travers RL, Betts JA, Thompson D, Walhin J-P, Wallis GA, Hamilton DL, Stevenson EJ, Tipton KD, Gonzalez JT (2019) Skipping breakfast before exercise creates a more negative 24-h energy balance: A randomized controlled trial in healthy physically active young men. Journal of Nutrition 149(8):1326-1334. doi: 10.1093/jn/nxz018.

This study characterised muscle glycogen utilization and substrate balance during cycling in a fasted- and in a fed-state.

*10. Impey SG, Jevons E, Mees G, Cocks M, Strauss J, Chester N, Laurie I, Target D, Hodgson A, Shepherd SO, Morton JP (2020) Glycogen Utilization during Running: Intensity, Sex, and Muscle-Specific Responses. Med Sci Sports Exerc 52 (9):1966-1975. doi:10.1249/MSS.0000000000002332.

This study characterized muscle glycogen utilization rates during different patterns of exercise.

11. Thomas DT, Erdman KA, Burke LM (2016) American College of Sports Medicine Joint Position Statement. Nutrition and Athletic Performance. Med Sci Sports Exerc 48 (3):543-568. doi:10.1249/MSS.0000000000000852

*12. Craven J, Desbrow B, Sabapathy S, Bellinger P, McCartney D, Irwin C (2021) The Effect of Consuming Carbohydrate With and Without Protein on the Rate of Muscle Glycogen Re-synthesis During Short-Term Post-exercise Recovery: a Systematic Review and Meta-analysis. *Sports Med Open* 7 (1):9. doi:10.1186/s40798-020-00297-0

This meta-analysis shows that protein co-ingestion with carbohydrate does not further accelerate post-exercise muscle glycogen repletion when carbohydrate intakes are above ~1 g per kg body mass per hour.

13. Fuchs CJ, Gonzalez JT, Beelen M, Cermak NM, Smith FE, Thelwall PE, Taylor R, Trenell MI, Stevenson EJ, van Loon LJ (2016) Sucrose ingestion after exhaustive exercise accelerates liver, but not muscle glycogen repletion compared with glucose ingestion in trained athletes. *J Appl Physiol* (1985) 120 (11):1328-1334. doi:10.1152/jappphysiol.01023.2015

14. Decombaz J, Jentjens R, Ith M, Scheurer E, Buehler T, Jeukendrup A, Boesch C (2011) Fructose and galactose enhance postexercise human liver glycogen synthesis. *Med Sci Sports Exerc* 43 (10):1964-1971. doi:10.1249/MSS.0b013e318218ca5a

15. Roden M, Perseghin G, Petersen KF, Hwang JH, Cline GW, Gerow K, Rothman DL, Shulman GI (1996) The roles of insulin and glucagon in the regulation of hepatic glycogen synthesis and turnover in humans. *J Clin Invest* 97 (3):642-648. doi:10.1172/JCI118460

16. Maunder E, Podlogar T, Wallis GA (2018) Postexercise Fructose-Maltodextrin Ingestion Enhances Subsequent Endurance Capacity. *Med Sci Sports Exerc* 50 (5):1039-1045. doi:10.1249/MSS.0000000000001516

*17. Podlogar T, Wallis GA (2020) Impact of Post-Exercise Fructose-Maltodextrin Ingestion on Subsequent Endurance Performance. *Front Nutr* 7:82. doi:10.3389/fnut.2020.00082

This study demonstrated that fructose-maltodextrin co-ingested during post-exercise recovery increases ingested carbohydrate oxidation rates in subsequent exercise, without affecting subsequent time-trial performance.

*18. Hengist A, Watkins JD, Smith HA, Edinburgh RM, Betts JA, Roe GAB, Gonzalez J (2020) The effects of glucose-fructose co-ingestion on repeated performance during a day of intensified rugby union training in professional academy players. J Sports Sci:1-9. doi:10.1080/02640414.2020.1860473

This study demonstrated that fructose-maltodextrin and protein co-ingested between two intensified rugby union training sessions did not improve performance in the second session compared with maltodextrin and protein alone.

19. Stellingwerff T, Morton JP, Burke LM (2019) A Framework for Periodized Nutrition for Athletics. Int J Sport Nutr Exerc Metab 29 (2):141-151. doi:10.1123/ijsnem.2018-0305

**20. Podlogar T, Free B, Wallis GA (2020) High rates of fat oxidation are maintained after the sleep low approach despite delayed carbohydrate feeding during exercise. Eur J Sport Sci:1-11. doi:10.1080/17461391.2020.1730447

This study demonstrates that high whole-body fat oxidation rates can be sustained after commencing exercise with low carbohydrate availability, even with carbohydrate feeding during exercise is permitted as long as feeding is delayed by ~1 hour. This provides an approach to facilitate training volume and intensity whilst permitting high fat oxidation and potentially altered cell signalling.

*21. Edinburgh RM, Bradley HE, Abdullah N-F, Robinson SL, Chrzanowski-Smith OJ, Walhin J-P, Joannis S, Manolopoulos KN, Philp A, Hengist A, Chabowski A, Brodsky FM, Koumanov F, Betts JA, Thompson D, Wallis GA, Gonzalez JT (2020) Lipid metabolism links nutrient-exercise timing to insulin sensitivity in men classified as overweight or obese. J Clin Endocrinol Metab. 2020 Mar 1;105(3):660-76. doi: 10.1210/clinem/dgz104.

This study demonstrated that ingesting carbohydrate before each exercise session blunted exercise-related adaptation in skeletal muscle during 6-weeks of training compared to overnight fasting.

*22. Edinburgh RM, Koumanov F, Gonzalez JT (2021) Impact of pre-exercise feeding status on metabolic adaptations to endurance-type exercise training. J Physiol. doi:10.1113/JP280748

This paper reviewed the effects of feeding and fasting prior to exercise on metabolic adaptations.

**23. Hearris MA, Hammond KM, Seaborne RA, Stocks B, Shepherd SO, Philp A, Sharples AP, Morton JP, Louis JB (2019) Graded reductions in preexercise muscle glycogen impair exercise capacity but do not augment skeletal muscle cell signaling: implications for CHO periodization. J Appl Physiol (1985) 126 (6):1587-1597. doi:10.1152/jappphysiol.00913.2018

This study demonstrates that restricting carbohydrate intake can impair the capacity for exercise without altering muscle cell signalling, questioning the role of modest carbohydrate restriction for augmenting training-induced adaptations.

*24. Hearris MA, Owens DJ, Strauss JA, Shepherd SO, Sharples AP, Morton JP, Louis JB (2020) Graded reductions in pre-exercise glycogen concentration do not augment exercise-induced nuclear AMPK and PGC-1 α protein content in human muscle. Exp Physiol. doi:10.1113/EP088866

This study demonstrated that commencing exercise with lower muscle glycogen did not enhance skeletal muscle mRNA expression for proteins related to exercise adaptation.

25. Hammond KM, Sale C, Fraser W, Tang J, Shepherd SO, Strauss JA, Close GL, Cocks M, Louis J, Pugh J, Stewart C, Sharples AP, Morton JP (2019) Post-exercise carbohydrate and energy availability induce independent effects on skeletal muscle cell

signalling and bone turnover: implications for training adaptation. J Physiol 597 (18):4779-4796. doi:10.1113/JP278209.

This study demonstrated that commencing exercise with lower carbohydrate availability did not enhance skeletal muscle mRNA expression for proteins related to exercise adaptation but did alter bone turnover markers.

26. Yeo WK, Paton CD, Garnham AP, Burke LM, Carey AL, Hawley JA (2008) Skeletal muscle adaptation and performance responses to once a day versus twice every second day endurance training regimens. J Appl Physiol (1985) 105 (5):1462-1470. doi:10.1152/jappphysiol.90882.2008

27. Hulston CJ, Venables MC, Mann CH, Martin C, Philp A, Baar K, Jeukendrup AE (2010) Training with low muscle glycogen enhances fat metabolism in well-trained cyclists. Medicine & Science in Sports & Exercise 42 (11):2046-2055

*28. Areta JL, Iraki J, Owens DJ, Joannis S, Philp A, Morton JP, Hallén J (2020) Achieving energy balance with a high-fat meal does not enhance skeletal muscle adaptation and impairs glycaemic response in a sleep-low training model. Exp Physiol 105 (10):1778-1791. doi:10.1113/EP088795

This study demonstrated that the addition of fat to the diet during a period of low-carbohydrate availability does not increase mRNA expression of genes, or phosphorylation status of proteins relating to exercise adaptation.

29. Marquet LA, Brisswalter J, Louis J, Tiollier E, Burke LM, Hawley JA, Hausswirth C (2016) Enhanced Endurance Performance by Periodization of Carbohydrate Intake: "Sleep Low" Strategy. Med Sci Sports Exerc 48 (4):663-672. doi:10.1249/MSS.0000000000000823

30. Burke LM, Ross ML, Garvican-Lewis LA, Welvaert M, Heikura IA, Forbes SG, Mirtschin JG, Cato LE, Strobel N, Sharma AP, Hawley JA (2017) Low carbohydrate, high fat diet impairs exercise economy and negates the performance benefit from intensified training in elite race walkers. J Physiol 595 (9):2785-2807. doi:10.1113/JP273230

****31.** Burke LM, Sharma AP, Heikura IA, Forbes SF, Holloway M, McKay AKA, Bone JL, Leckey JJ, Welvaert M, Ross ML (2020) Crisis of confidence averted: Impairment of exercise economy and performance in elite race walkers by ketogenic low carbohydrate, high fat (LCHF) diet is reproducible. PLoS One 15 (6):e0234027. doi:10.1371/journal.pone.0234027
This study demonstrated that the impairment in endurance exercise performance with low-carbohydrate diets is repeatable, and that periodised carbohydrate intakes are broadly comparable to high-carbohydrate intakes for exercise performance in well-trained athletes. This highlights the importance of carbohydrate availability for performance and questions whether periodised carbohydrate intakes provide further benefit.

32. Burke LM, Sharma AP, Heikura IA, Forbes SF, Holloway M, McKay AKA, Bone JL, Leckey JJ, Welvaert M, Ross ML (2020) Correction: Crisis of confidence averted: Impairment of exercise economy and performance in elite race walkers by ketogenic low carbohydrate, high fat (LCHF) diet is reproducible. PLoS One 15 (6):e0235592. doi:10.1371/journal.pone.0235592

***33.** Burke LM, Whitfield J, Heikura IA, Ross MLR, Tee N, Forbes SF, Hall R, McKay AKA, Wallett AM, Sharma AP (2020) Adaptation to a low carbohydrate high fat diet is rapid but impairs endurance exercise metabolism and performance despite enhanced glycogen availability. J Physiol. doi:10.1113/JP280221

This study demonstrated that chronic low carbohydrate availability can rapidly increase fat oxidation during exercise, and impair exercise capacity even when carbohydrate availability is acutely restored.

Figure Legends

Figure 1. Post-exercise muscle (**A**) and liver (**B**) glycogen repletion rates with ingestion of large amounts ($>0.9 \text{ g} \cdot \text{kg}^{-1} \cdot \text{h}^{-1}$) of carbohydrates as either glucose-based carbohydrates, or glucose-fructose (sucrose) mixtures. Data are all means \pm 95%CI, and in panel **A** are redrawn from reference 8; data in panel **B** are pooled from references 13 and 14.

Figure 2. Data from studies in endurance athletes undergoing training with either continuously high carbohydrate availability (High-CHO), periodised-carbohydrate availability (Periodised-CHO), or chronically low-carbohydrate availability (High-Fat, Low-CHO). Data presented as the means \pm SD from each study (**A**) and also as the weighted-mean and weighted-SD (weighted based on sample size) for fat oxidation rates (**B**) and performance (**C**). Data from references 28, 30, 33-35.

Table Legends

Table 1. Effects of isocaloric post-exercise feeding of glucose plus fructose-based *versus* glucose only-based carbohydrates on subsequent exercise performance.